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A STUDY OF THE DOUBLE VENTURI PRINCIPLE IN ITS APPLICATION TO HIGH SPEED WIND TUNNELS

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A STUDY OF THE DOUBLE VENTURI PRINCIPLE

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Preface

Meaning of Symbols Used

h_{qv_T} - dynamic pressure in test section of double venturi including tare, MM water

h_{qv} - net dynamic pressure in test section of double venturi, MM water

h'_s - static pressure in small tunnel, MM Alcohol

h'_{qD} - dynamic pressure in duct upstream of double venturi, MM Alcohol.

℄ - Centerline of duct where 1" ℄ means 1 inch from the duct centerline etc.

h'_{sD_1} - static pressure in duct upstream of double venturi, MM Alcohol

h'_{sD_2} - static pressure in duct downstream of double venturi, MM Alcohol.

Δp_D - static pressure drop through duct, MM Alcohol.

$\Delta p_T = h'_{sD_1} - h'_{sD_2}$

$\Delta p = \Delta p_T - \Delta p_D$

E.R. - energy ratio--ratio of kinetic energy in the air in test section to the sum of all the losses.

u - velocity in test section of double venturi

U_D - velocity in duct upstream of double venturi

A Study of the Double Venturi Principle in its Application to High-Speed Wind Tunnels

I Summary

A number of variations of double venturis were tested in a 6-inch diameter duct in order to determine the maximum velocity increase in the forward, or primary, venturi and the power required, with an aim towards using the double venturi to achieve a small area, high-velocity region from a large area, low-velocity region.

It was found that the double venturi could be used to obtain velocity increases of the order of four and a half times that obtained in a low-speed test section. It was also observed that the horsepower required would probably not be excessive.

II Introduction

A double venturi consists of an arrangement of two venturi tubes, one larger than the other, such that the discharge of the smaller or primary venturi will exit into the throat of the larger or secondary venturi. By placing this double venturi into a stream of air it is possible to obtain extremely low pressures[1] in the throat of the primary venturi, much lower in fact than would have been experienced if only the primary venturi was placed in the air stream. Since it is known from Bernoulli's theorem that pressure decreases are accompanied by velocity increases, this double venturi principle gives rise to the possibility that it may prove useful as a source of high velocity air for wind tunnel testing.

The high operating speed range maintained by present day aircraft makes it essential that wind tunnel tests of various components including the entire airplane be made at Mach numbers approaching unity, where the Mach number is the ratio of the local velocity to the local acoustic velocity. Wind tunnels capable of attaining such high velocities are extremely expensive and consequently many institutions, through lack of funds, are hampered in their high speed research.

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[1] John K. Vennard, Elementary Fluid Mechanics, First Edition, (New York: John Wiley and Sons, 1940), p. 246

Bailey and Wood[2,3], in England, successfully created high velocities by using the inductive action of the discharge from a compressed air tunnel. An annular nozzle was mounted about a working section 2¼ inches in diameter with a parallel portion 1 inch long. High pressure air (50-90 psi.) was then discharged through the annular gap on the downstream side of the test section. This high pressure air passing along the downstream side of the test section caused an induced flow in the working section. Many variations of test section length and annular gap were tested and speeds as high as 950 feet per second were observed in the test section.

A similar approach is that of using a low-speed wind tunnel to furnish the power to drive the air through a double venturi with the idea of creating high velocities in the test section of the primary venturi. The double venturi, if properly adapted, could conceivably meet this requirement, and the simplicity of such an arrangement is readily evident.

With this idea in mind, a study of this principle was initiated to determine the feasibility of such an arrangement for the Georgia Tech 9-foot wind tunnel. It was decided that

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[2]A. Bailey and S. A. Wood, Development of a High Speed Induced Wind Tunnel, Aeronautical Research Committee Reports and Memoranda, No. 1468, 1933.

[3]A. Bailey and S. A. Wood, Development of a High Speed Induced Wind Tunnel of Rectangular Cross-Section, Aeronautical Research Committee Reports and Memoranda, No. 1791, 1937.

a model of such an arrangement be tested in the small wind tunnel as a preliminary study. To reproduce the actual conditions as closely as possible, a double venturi model was placed inside a duct that was used to represent the circular test section of the large wind tunnel. The source of air was the Georgia Tech $2\frac{1}{2}$-foot tunnel. At a given tunnel speed the velocities inside the duct and inside the test section of the double venturi could be measured and the ratio of test section velocity to duct velocity could be calculated. This velocity ratio would give an indication of how a velocity might be expected in the test section of the full scale venturi for a given speed in the 9-foot wind tunnel.

Apparatus

The source of power for all tests was the Georgia Tech small wind tunnel. It has a $2\frac{1}{2}$-foot square jet and is of the Göttingen single-return type.

The duct, representing the 9 foot jet of the large wind tunnel, was made out of ordinary 6 inch diameter stovepipe 36 inches long. This duct was then cut into two sections, the smaller one being 13 inches long. This smaller section of pipe was to be permanently mounted in the center of the rear end of the test section of the small wind tunnel while the longer, forward portion could be removed quite readily. The double venturi was placed in the forward portion so that different configurations could be easily effected by removing the forward portion, adjusting the double venturi, and then replacing the complete unit. The venturis were mounted in the duct by means of metal straps as shown in Fig. 1.

Small holes were drilled through the strap flanges and through the duct so that the strap could be fastened to the duct by nuts and bolts. The holes were located such that the venturi would be symmetrically mounted in the duct. Two narrow slots were cut at the top and bottom of the duct positioned so that the strap holding the primary venturi could be moved fore and aft along the duct longitudinal axis. The position of the primary venturi in relation to the stationary secondary venturi could then be varied simply by loosening the nuts holding the primary venturi strap, moving the primary venturi to the desired position, and then retightening the nuts to keep the primary venturi firmly in place during the test.

The duct was mounted in the test section as shown in Fig. 2. The tension in the front cables was adjusted by means of turn buckles.

For the initial test five primary venturis and one secondary venturi were constructed. They were all made out of mahogany and will hereafter be designated as follows:

> Secondary Venturi - 4" x 2" meaning 4 inch outside diameter and 2" throat diameter. Enough information will be given so that an entire venturi could be constructed from just a single designation.
>
> Primary Venturis - 1-1/8 x 1/2
> 1-3/8 x 1/2
> 1-3/8 x 3/4
> 1-5/8 x 1/2
> 1-5/8 x 3/4

Each venturi consisted of entrance cone, throat, and divergent portion with each distinct portion requiring special consideration. The object of entrance cone design[4] is such that the curvature should be small enough so that the local velocities may not exceed the speed at the end of the cone. If

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[4]Hsue-Shen Tsien, On The Design of The Contraction Cone For a Wind Tunnel, Journal of the Aeronautical Sciences, Vol. 10, pp. 68-70, February, 1943.

the curvature is large there may be regions of adverse pressure gradient and there would be great possibility of separation in the boundary layer. Hence the design should be such that the velocity increases monotonically from the beginning to end. It then follows that the pressure decreases monotonically. The shape of the entrance cone for all primary venturis was plotted as outlined in the paper by Smith and Wang[5], for cone length equal to one throat diameter, while the entrance cone for the secondary venturi was obtained from Tsien's[6] paper, cone length equal to two throat diameters. The primary venturi entrance cones had a uniformity of throat speeds within 1%.

The straight portion, or test section, of the primary venturi was arbitrarily chosen as the diameter of the throat. The question now arises as to what straight portion, if any, should be included in the secondary venturi. There is the possibility that no straight portion is necessary in which case the secondary venturi would be shorter hence have less skin friction drag. However, since the discharge from the

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[5]Richard H. Smith and Chi-Teh Wang, <u>Contracting Cones Giving Uniform Throat Speeds</u>, Journal of the Aeronautical Sciences, p. 356, October, 1944

[6]Tsien, <u>loc</u>. <u>cit</u>.

primary venturi has to mix with the surrounding air from the secondary entrance cone, there is a very strong possibility that separation would take place if this mixture of air of varying velocities were immediately diffused. Hence it is desirable to have this mixture pass through a straight portion in an attempt to get uniform flow before diffusion takes place. The straight portion of the secondary venturi was chosen to be equal to its throat diameter.

The diffuser is a device whereby fluid passing through it will experience a regain in static pressure. Losses in a diffuser are composed of friction loss and expansion losses, both dependent upon the shape of the enlargement. Gibson[7] did early work on losses in diffuser tubes and he expresses the loss as a function of a loss cofficient, K_L, such that an increase in K_L means an increase in total loss. K_L is primarily dependent upon the cone angle and is a function of the area ratio but only for cone angles exceeding about 22°. If an extremely small angle is used, K_L is pratically all skin friction while with large angles the abrupt enlargement causes separation and turbulence thus consuming a great deal

[7]Gibson, Hydraulics and Its Applications (New York: D. Van Nostrand Co., 1930), p. 93

of energy. It is then desirable to obtain the angle that gives the least skin friction loss. From Fig. 43 in Gibson[8], also reproduced in Vennard[9], K_L is a minimum at a cone angle of 7°. This diffuser angle was used on the primary venturis. In an attempt to keep the secondary venturi from becoming excessively long the diffuser angle was set at 9°. This decision was reached on the belief that the discharged air of the primary venturi would have a boundary layer effect upon the secondary venturi such that separation would be delayed.

IV Procedure

Three distinct types of experiments were performed.

a. Velocity in throat of primary venturi
b. Velocity in duct upstream of double venturi
c. Static pressure drop between upstream and downstream ends of double venturi.

The generalized procedure will be given for all three type tests. Each specific configuration was tested in like manner.

In obtaining the velocity in the throat of the primary venturi it would have been desirable to have inserted a pitot-static tube in the throat, but because of the very limited

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[8] Gibson, <u>loc</u>. <u>cit</u>.

[9] Vennard, <u>op</u>. <u>cit</u>. p. 173

space another means of obtaining the dynamic pressure was used. A 1/16" diameter piece of copper tubing was inserted into the throat and bent at 90° so that the opening of the tube inside the venturi was parallel to the longitudinal axis and open to the airstream. This tube would measure the total pressure in the center of the throat. The static pressure in the throat could be obtained by drilling a small hole from the outer surface down to the throat of the venturi and measuring the pressure at the flush orifice in the throat. A water manometer was used to record pressures and it consisted of a bottle with an additional opening to the atmosphere besides the neck, and a 6-foot meter stick. A piece of glass tubing about 4 inches long was inserted about half way into the bottle stopper and the stopper in turn was placed into the neck of the semi-filled bottle. The interior end of the glass tubing was immersed in the water. Saran tubing was connected to the exposed end of the glass tubing and the Saran was placed against the meter stick which was now placed in a vertical position. The static pressure line from the primary venturi was connected to the open end of the Saran tubing while the total pressure line was connected to the bottle opening that was exposed to the atmosphere as shown in Fig. 3. In effect this set-up acted as a pitot-static tube. The water level in the Saran tubing would indicate the difference between the total pressure and the static pressure. This difference is the dynamic pressure.

At a given tunnel speed, the dynamic pressure in the test section of the double venturi could then be read in millimeters of water. Rather than determine the velocity ratio i.e. ratio of velocity in throat of primary venturi to velocity in duct, at only one tunnel speed, it was felt that a large range of tunnel speeds would give an indication of the constancy of the velocity ratio. Hence the tunnel speed was varied from about 40-90 feet per second with venturi dynamic pressure readings being taken at each new tunnel speed.

A pitot-static tube was used to determine the dynamic pressure upstream of the double venturi. This tube was placed in the duct about 6 inches ahead of the primary venturi. The pitot-static tube was connected to manometer and the dynamic pressure was recorded in millimeters of alcohol, Fig. 4. Since the velocity distribution across the duct was problematical, it was felt that readings at more than one station should be taken. It was assumed that the distribution would be symmetrical about the axis. Readings on the horizontal axis through the duct were taken at points 1 inch and 2 inches from the vertical centerline. Since the variation was so slight it was assumed that the mean velocity was the linear average between the two. As a verification of the two readings at the different stations intermittent readings

2-3/4 inches from the vertical centerline were observed and these checked extremely close to the others. These 2-3/4 inch readings were not recorded.

The static pressure upstream of the double venturi was found by means of a pitot-static tube. In these test, however, only the static line from the pitot was connected to one end of an alcohol manometer. The other end of the manometer was open to the atmosphere. The static pressure upstream of the double venturi was observed to be above atmospheric. The procedure for obtaining the static pressures was the same as that employed in the previous test to obtain the dynamic pressure. Readings were taken 1 inch and 2 inches from the vertical centerline and the mean static pressure was assumed to be the linear average.

The static pressure downstream of the double venturi was found by placing the pitot-static tube about 8-10 inches behind the secondary venturi and repeating the procedure as outlined previously. However, due to the mixture of air from the diffuser and that from between the secondary venturi and the duct, another reading at 2-3/4 inches from the centerline was recorded. These static pressures were found to be below atmospheric. The algebraic difference between the two static pressures will give the total static pressure drop through the double venturi and duct. To find the static pressure drop due solely to the double venturi, the loss in head through the duct must be known. The duct was mounted in the jet with the double venturi removed. The same procedure as previously employed was used to find the pressure drop through the duct due to skin friction. The static pressure of the double venturi is then the difference between the total static pressure drop and the duct static pressure drop.

V Results and Discussion

In all tests the duct diameter and the dimensions of the secondary venturi remained constant. This condition reduced the number of varying parameters quite considerably and left two important ones to be considered. These are the variation of test section or jet area with constant "slot" area, and the variation of "slot" area with constant jet area. The "slot" referred to is the area between the outside diameter of the primary venturi and the throat diameter of the secondary venturi. Each primary venturi was placed so that its discharge end was concentrically located at the entrance of the throat of the secondary venturi. Slight variations of position of the primary venturi fore and aft along its centerline apparently produced very slight changes in velocity ratio of the double venturi. This type of investigation was not rigorously carried out, but it was observed that a few arbitrary variations produced little change.

Since the results of this investigation were to be used for further study on the full scale model, it was necessary to express all parameters as dimensionless ratios. The following ratios were chosen for it was believed that they could readily be expanded to the full scale model.

a. Ratio of area of entrance cone to area of throat of secondary venturi $\frac{A_c}{A_T}$

b. Ratio of area of annulus between secondary venturi and duct to area of duct $\frac{A_{SD}}{A_D}$.

c. Ratio of area of "slot" to area of throat of secondary venturi $\frac{A_S}{A_T}$

d. Ratio of area of test section to area of duct $\frac{A_J}{A_D}$

As mentioned previously only five primary venturis were constructed. These five supplied three different values of $\frac{A_J}{A_D}$. However, the different values of $\frac{A_S}{A_T}$ were too few so the following procedure was adopted. When a certain value of $\frac{A_S}{A_T}$ was required for a given value of $\frac{A_J}{A_D}$, a primary venturi with proper $\frac{A_J}{A_D}$ was reduced in outside diameter. The limitation in this procedure is readily seen in that $\frac{A_S}{A_T}$ could only be increased because cutting down the outside dimensions of the primary venturi resulted in an increase in A_S. All tests conducted in this investigation were made at $\frac{A_C}{A_T} = 4.$ and $\frac{A_{SD}}{A_D} = 0.576$. Hence for any corresponding values of $\frac{A_S}{A_T}$ and $\frac{A_J}{A_D}$ obtained from Figs. 5-7 and the area of the full scale low speed tunnel test section, all dimensions of the double venturi could be calculated.

Figs. 5, 6, 7 are plotted with constant $\frac{A_J}{A_D}$ lines as variations of $\frac{u}{U_D}$, $\frac{\Delta p}{q}$ and E.R. with $\frac{A_S}{A_T}$ respectively ($\frac{u}{U_D}$ and $\frac{\Delta p}{q}$ are average values while E.R. was calculated at max. h's.) From Fig. 5 it is seen that the same $\frac{u}{U_D}$ exists for two differing values of $\frac{A_S}{A_T}$ with constant $\frac{A_J}{A_D}$. However, Fig. 6 shows that for the same value of $\frac{u}{U_D}$ the larger value of $\frac{A_S}{A_T}$ has a lower value of $\frac{\Delta p}{q}$. Expressed as a loss, this lower value of $\frac{\Delta p}{q}$ would mean a lower loss thereby requiring less horsepower output to obtain the same velocity ratio for a given jet area. Hence for the same values of $\frac{u}{U_D}$ for constant $\frac{A_J}{A_D}$, $\frac{\Delta p}{q}$ decreases as $\frac{A_S}{A_T}$ increases. Fig. 5 shows that of all venturis tested the ones with greatest $\frac{A_J}{A_D}$ showed the best $\frac{u}{U_D}$ for constant $\frac{A_S}{A_T}$. If $\frac{A_J}{A_D}$ keeps increasing it will gradually approach the condition where the primary venturi will be a straight pipe. Hence it was desirable to determine if $\frac{u}{U_D}$ kept increasing with $\frac{A_J}{A_D}$. At $\frac{A_S}{A_T} = 0.608$ a venturi was tested with $\frac{A_J}{A_D} = 0.0278$ and it was found that $\frac{u}{U_D}$ fell off to $\frac{u}{U_D} = 3.30$. This substantiated the belief that a properly designed primary venturi would be more beneficial than a straight pipe.

Fig. 6 shows that for constant $\frac{A_J}{A_D}$, $\frac{\Delta p}{q}$ is reduced as $\frac{A_S}{A_T}$ is increased. This is quite understandable. What actually occurs is that for a given A_J the outside diameter of the primary venturi is reduced so as to increase $\frac{A_S}{A_T}$. This reduction in outside diameter reduced the total length of the primary venturi and as can be shown from Wattendorf's[10] work the losses will be lowered. Another way of comparing losses is that of comparing energy ratios of the configuration in question. The energy ratio is the ratio of the kinetic energy of the air in the test section to the sum of all the losses. This ratio is dimensionless. Fig. 7 shows that for constant $\frac{A_J}{A_D} = 0.00692$ an increase in $\frac{A_S}{A_T}$ results in increased E.R. For $\frac{A_J}{A_D} = 0.01082$ the E.R. decreases with $\frac{A_S}{A_T}$ increase until a minimum E.R. = 0.78 at $\frac{A_S}{A_T} = 0.608$ is reached, then it increases. For $\frac{A_J}{A_D} = 0.01558$ the minimum E.R. = 0.89 is reached at $\frac{A_S}{A_T} = 0.435$ and then increases to a maximum E.R. = 1.55 at $\frac{A_S}{A_T} = 0.608$ before falling off again. Also from Fig. 7 it is seen that for constant $\frac{A_S}{A_T}$ the energy ratio increases with increasing $\frac{A_J}{A_D}$.

As can be seen from the three curves the values of $\frac{A_S}{A_T}$ between 0.5 and 0.6 for $\frac{A_J}{A_D} = 0.01082$ appear to be inconsistent with existing data. However, these points were rechecked and found to be experimentally correct. The possibility might conceivably exist, though, whereby this range of $\frac{A_S}{A_T}$ is so critical for this particular $\frac{A_J}{A_D}$ that these tests should have been made at very much smaller increments of $\frac{A_S}{A_T}$.

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[10] F. L. Wattendorf, Factors Influencing the Energy Ratio of Return Flow Wind Tunnels, Fifth International Congress for Applied Mechanics p. 526 Cambridge, 1938

Referring to the duct velocities, h'_{q_D} as shown in Tables I-XI, it is seen that there is a very iniform velocity distribution in the duct upstream of the double venturi. Tables XII-XXII show that the static pressure in the duct downstream of the double venturi gives indications of a fairly uniform velocity distribution with a tendency toward an increase in velocity as the distance from the centerline is increased. Tables I-XI also show that for the variation in tunnel speeds the velocity ratio, $\frac{u}{U_D}$, is very constant with the maximum variation in $\frac{u}{U_D}$ of the order of 3%.

VI Conclusions

A double venturi, when placed in a low speed test section can be used to create high speeds within the throat of the primary venturi. These speed increases are of the order of four and a half times the speed of the test section. The maximum velocity ratio obtained in these tests was 5.

The velocity ratio is very constant for varying tunnel speeds, or, within the range investigated, varying Reynolds numbers.

For the same velocity ratio at constant jet-duct ratio the configuration with larger slot area would have a lower loss.

In general an increase in slot area results in lower losses and higher energy ratios.

It must be remembered that all tests conducted in this investigation were made at constant $\frac{A_{SD}}{A_D}$, hence further studies might possibly keep other parameters constant while varying $\frac{A_{SD}}{A_D}$.

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APPENDIX

Sample Calculations and Formulae

$$h_{q_D} = h'_{q_D} \times \text{Specific Gravity of Alcohol used}$$

$$h_{q_D} = h'_{q_D} \times 0.816$$

$$h_{q_D} = \frac{\rho}{2} U_D^2$$

$$h_{q_v} = \frac{\rho}{2} u^2$$

$$\therefore \frac{u}{U_D} = \sqrt{\frac{h_{q_v}}{h_{q_D}}}$$

Determination of Energy Ratio

$$E.R. = \frac{\text{Useful Power in Test Section}}{\text{Horsepower Loss}}$$

$$E.R. = \frac{\rho/2\, u^3 A_J}{U_D A_D \Delta p}$$

Where the units are such that E.R. is dimensionless

This expression can be written as

$$E.R. = \frac{u\, q_v A_J}{U_D \Delta p A_D}$$

Since Δp is in MM Alcohol

$$\Delta p \times 0.816 = \Delta p \text{ MM } H_2O$$

Then q_v in $\#/ft^2$ will be used in the above equation as h_{q_v} in MM H_2O

Thus

$$\text{E.R.} = \left(\frac{\mu}{U_D}\right)\left(\frac{h_{qv}}{\Delta p}\right)\left(\frac{A_J}{A_D}\right)$$

Determination of Ratios

Duct Diameter = 6"

$A_D = \frac{\pi}{4}(36) = 28.3$ in.

O.D. Secondary Venturi = 4"

$A = \frac{\pi}{4}(16) = 12.58$ in.

$$\frac{A_{SD}}{A_D} = \frac{(28.3 - 12.58)}{(28.3)} = \frac{15.72}{28.3} = 0.576$$

Jet Sizes

1/2" Dia. $\quad A_J = \frac{\pi}{4}(.5)^2 = 0.1962\ .in^2$

5/8" Dia. $\quad A_J = \frac{\pi}{4}(.625)^2 = 0.307\ .in^2$

3/4" Dia. $\quad A_J = \frac{\pi}{4}(.750)^2 = 0.441\ .in^2$

Jet Diameter	$\frac{A_J}{A_D}$
1/2"	0.00692
5/8"	0.01082
3/4"	0.01558

$$A_T = \frac{\pi}{4} D_T^2 = \frac{\pi}{4}(4) = 3.14\ in.^2$$

O.D. Primary Venturi	A	$A_S = A_T - A$	$\frac{A_S}{A_T}$
1.625	2.080	1.060	0.337
1.500	1.768	1.372	0.437
1.375	1.492	1.648	0.524
1.250	1.229	1.911	0.608
1.125	0.993	2.147	0.685

It will be shown now that horsepower requirements are not unreasonable. These calculations are qualitative rather than quantitative. This is due to the fact that $\frac{\Delta p}{q}$ for the full scale tests will actually be lower than indicated because of increased Reynolds Number. However, compressibility effects will be encountered which probably will reduce the efficiency.

Diameter test section Large Wind Tunnel = 9'

$$A_D = \frac{\pi}{4} (81) = 63.6 \text{ Ft.}^2$$

Average Atlanta Density ρ = 0.0022 Slugs/ft.^{3}

Assume Tunnel Run at $V = 100$ M.P.H.

and Loss of $\frac{\Delta p}{q} = 1.00$

From Fig. 6 for $\frac{\Delta p}{q} = 1.00$, $\frac{A_J}{A_D} = 0.01558$ at $\frac{A_S}{A_T} = 0.67$. This combination will give largest test section for given $\frac{\Delta p}{q}$.

Then from Fig. 5 at $\frac{A_J}{A_D} = 0.01558$ and $\frac{A_S}{A_T} = 0.67$, $\frac{u}{U_D} = 4.75$.

$$q = \frac{\rho}{2} V^2 = \left(\frac{.0022}{2}\right) (100)^2 (1.467)^2$$

$$q = 23.7 \text{ \#/ft.}^2$$

$$\frac{\Delta p}{q} = 1.00$$

$$\Delta p = (1.00)\ (23.7)$$

$$\Delta p = 23.7\ \#/\text{ft}^2$$

$$HP = \frac{A_D\, V\, \Delta p}{375}$$

where A_D is in ft.^{2}

V is M.P. H.

Δp is in #/ft.^{2}

$$HP = \frac{(63.6)\ (100)\ (23.7)}{375}$$

$$HP = 402$$

Size of Test Section

$$\frac{A_J}{A_D} = 0.01558$$

$$A_J = (0.01558)(63.6) = 0.99\ \text{ft.}^2$$

$$D_J = \sqrt{\frac{4}{\pi}\ (.99)} = \sqrt{1.26}$$

$$D_J = 1.12\ \text{ft.}$$

These calculations would indicate that further research on this subject should be performed in order to obtain more accuracy in predicting full scale data.

h'_s	$h_{q_{v_T}}$	h_{q_v}	h'_{q_o} 1" ℄	h'_{q_o} 2" ℄	h'_{q_o}	h_{q_o}	$\frac{u}{U_o}$
30.0	355	245	15.0	15.0	15.0	12.22	4.47
40.0	432	322	20.4	20.2	20.3	16.58	4.41
50.0	512	402	25.4	25.6	25.5	20.80	4.39
60.0	590	480	30.7	30.7	30.7	25.10	4.37
65.0	630	520	33.0	33.2	33.1	27.00	4.38
70.0	675	565	36.2	36.2	36.2	29.55	4.38

TABLE I

Double Venturi Velocity Ratio

1 1/2 x 3/4 Primary Venturi

h'_s	$h_{q_{v_T}}$	h_{q_v}	h'_{q_o} 1" ℄	h'_{q_o} 2" ℄	h'_{q_o}	h_{q_o}	$\frac{u}{U_o}$
30.0	405	295	16.2	16.2	16.2	13.20	4.58
40.0	505	395	22.3	21.9	22.1	18.02	4.69
50.0	605	495	27.9	27.7	27.8	22.65	4.67
60.0	700	590	33.6	33.2	33.4	27.25	4.65
65.0	747	637	36.1	36.3	36.2	29.50	4.63
70.0	792	682	39.0	39.2	39.1	31.90	4.63

TABLE II

Double Venturi Velocity Ratio

1 1/8 x 1/2 Primary Venturi

h'_s	h_{gv_T}	h_{gv}	h'_{go} 1" ℄	h'_{go} 2" ℄	h'_{go}	h_{go}	$\frac{u}{U_o}$
30.0	324	214	13.5	13.3	13.4	10.92	4.43
40.0	397	287	18.5	18.5	18.5	15.10	4.34
50.0	466	356	23.6	23.2	23.4	19.10	4.32
60.0	535	425	28.2	28.2	28.2	23.00	4.30
65.0	570	460	31.2	31.4	31.3	25.60	4.25
70.0	610	500	34.0	34.0	34.0	27.75	4.24

TABLE III

Double Venturi Velocity Ratio

1 3/8 x 1/2 Primary Venturi

h'_s	h_{gv_T}	h_{gv}	h'_{go} 1" ℄	h'_{go} 2" ℄	h'_{go}	h_{go}	$\frac{u}{U_o}$
30.0	386	276	14.3	14.3	14.3	11.68	4.87
40.0	482	372	19.5	19.7	19.6	16.00	4.83
50.0	578	468	25.1	24.9	25.0	20.40	4.78
60.0	676	566	30.1	30.1	30.1	24.60	4.78
65.0	722	610	32.7	33.1	32.9	26.85	4.76
70.0	767	657	35.1	35.3	35.2	28.70	4.77

TABLE IV

Double Venturi Velocity Ratio

1 3/8 x 5/8 Primary Venturi

h'_s	h_{qv_T}	h_{qv}	h'_{qo} 1" ℄	h'_{qo} 2" ℄	h'_{qo}	h_{qo}	$\frac{u}{U_0}$
30.0	308	198	11.9	12.1	12.0	9.78	4.51
40.0	373	263	16.2	16.2	16.2	13.21	4.47
50.0	443	333	20.5	20.3	20.4	16.64	4.47
60.0	516	406	24.9	24.5	24.7	20.18	4.47
65.0	548	438	27.2	27.0	27.1	22.10	4.45
70.0	581	471	29.3	28.7	29.0	23.65	4.47

TABLE V

Double Venturi Velocity Ratio

1 5/8 x 1/2 Primary Venturi

h'_s	h_{qv_T}	h_{qv}	h'_{qo} 1" ℄	h'_{qo} 2" ℄	h'_{qo}	h_{qo}	$\frac{u}{U_0}$
30.0	365	255	13.4	13.4	13.4	10.92	4.83
40.0	452	342	18.5	18.7	18.6	15.1[illegible]	4.74
50.0	[illegible]	450	23.5	23.1	[illegible]	[illegible]	4.76
60.0	623	513	28.0	28.4	28.2	23.00	4.74
65.0	676	566	30.2	30.4	30.3	24.70	4.78
70.0	720	610	32.4	32.2	32.3	23.35	4.81

TABLE VI

Double Venturi Velocity Ratio

1 5/8 x 3/4 Primary Venturi

h'_s	h_{qv_T}	h_{qv}	h'_{qo} 1" ℄	h'_{qo} 2" ℄	h'_{qo}	h_{qo}	$\frac{u}{U_o}$
30.0	452	342	17.2	17.2	17.2	14.02	4.92
40.0	558	448	23.0	23.0	23.0	18.75	4.90
50.0	682	572	28.5	28.7	28.6	23.30	4.95
60.0	792	682	34.6	34.4	34.5	28.10	4.94
65.0	852	742	37.2	37.4	37.3	30.40	4.95
70.0	895	785	39.8	40.0	39.9	32.50	4.91

TABLE VII

Double Venturi Velocity Ratio

1 1/4 x 3/4 Primary Venturi

h'_s	h_{qv_T}	h_{qv}	h'_{qo} 1" ℄	h'_{qo} 2" ℄	h'_{qo}	h_{qo}	$\frac{u}{U_o}$
30.0	415	305	19.6	19.6	19.6	15.99	4.37
40.0	528	418	25.9	25.7	25.8	21.15	4.43
50.0	630	520	32.5	32.5	32.5	26.50	4.42
60.0	736	626	38.8	38.8	38.8	31.65	4.43
65.0	788	678	41.7	41.5	41.6	33.95	4.46
70.0	837	727	44.9	45.1	45.0	36.70	4.44

TABLE VIII

Double Venturi Velocity Ratio

1 1/8 x 5/8 Primary Venturi

h'_s	h_{qv_T}	h_{qv}	h'_{qo} 1" ℄	h'_{qo} 2" ℄	h'_{qo}	h_{qo}	$\frac{u}{U_o}$
30.0	352	242	17.8	18.0	17.9	14.60	4.08
40.0	452	342	24.0	24.2	24.1	19.70	4.16
50.0	543	433	29.8	30.0	29.9	24.40	4.21
60.0	625	515	36.0	36.2	36.1	29.45	4.18
65.0	670	560	38.8	39.0	38.9	31.80	4.19
70.0	710	600	41.6	41.8	41.7	34.10	4.19

TABLE IX

Double Venturi Velocity Ratio

1 1/4 x 5/8 Primary Venturi

h'_s	h_{qv_T}	h_{qv}	h'_{qo} 1" ℄	h'_{qo} 2" ℄	h'_{qo}	h_{qo}	$\frac{u}{U_o}$
30.0	432	322	16.1	16.1	16.1	13.13	4.94
40.0	544	434	21.2	21.2	21.2	17.31	4.99
50.0	660	550	26.5	26.5	26.5	21.35	5.04
60.0	772	662	32.0	32.2	32.1	26.20	5.03
65.0	822	712	35.2	35.0	35.1	28.65	4.98
70.0	867	757	37.2	37.2	37.2	30.35	4.99

TABLE X

Double Venturi Velocity Ratio

1 3/8 x 3/4 Primary Venturi

h'_s	h_{qv_T}	h_{qv}	h'_{qo} 1" ℄	h'_{qo} 2" ℄	h'_{qo}	h_{qo}	$\frac{u}{U_o}$
30.0	268	158	18.1	18.5	18.3	14.92	3.26
40.0	321	211	23.8	24.2	24.0	19.58	3.28
50.0	375	265	30.0	30.2	30.1	24.50	3.29
60.0	427	317	35.8	35.8	35.8	29.20	3.30
65.0	451	341	38.7	38.9	38.8	31.65	3.28
70.0	482	372	41.2	41.2	41.2	33.60	3.32

TABLE XI

Double Venturi Velocity Ratio

1 1/4 x 1 Primary Venturi

h'_s	h'_{so_1} 1" ℄	h'_{so_1} 2" ℄	h'_{so_1}	h'_{so_2} 1" ℄	h'_{so_2} 2" ℄	h'_{so_2}	Δp_o
30.0	-2.6	-2.8	-2.7	-7.4	-8.4	- 7.9	5.2
40.0	-3.7	-3.7	-3.7	-11.3	-11.5	-11.4	7.7
50.0	-4.6	-4.8	-4.7	-13.8	-14.4	-14.1	9.4
60.0	-5.4	-5.6	-5.5	-16.8	-16.8	-16.8	11.3
65.0	-6.1	-6.3	-6.2	-18.4	-18.4	-18.4	12.2
70.0	-6.6	-6.8	-6.7	-19.9	-20.1	-20.0	13.3

TABLE XII

Pressure Drop Through Duct

h'_s	h'_{SO_1} 1" ℄	h'_{SO_1} 2" ℄	h'_{SO_1}	h'_{SO_2} 1" ℄	h'_{SO_2} 2" ℄	h'_{SO_2} 2 3/4" ℄	h'_{SO_2}	Δp_T	Δp	$\frac{\Delta p}{q_0}$
30.0	17.7	17.7	17.7	-10.0	-10.5	-11.1	-10.5	28.2	23.0	1.715
40.0	23.2	23.2	23.2	-13.1	-13.6	-14.5	-13.7	36.9	29.2	1.580
50.0	28.8	29.2	29.0	-16.6	-17.3	-18.6	-17.5	46.5	37.1	1.583
60.0	34.6	34.4	34.5	-20.1	-21.1	-22.3	-21.2	55.7	44.4	1.575
65.0	37.1	36.9	37.0	-22.0	-22.8	-24.0	-22.9	59.9	47.7	1.525
70.0	40.0	40.0	40.0	-23.5	-24.2	-25.8	-24.5	64.5	51.2	1.505

TABLE XIII
Double Venturi $\Delta p/q_0$
1 3/8 x 1/2 Primary Venturi

h'_s	h'_{SO_1} 1" ℄	h'_{SO_1} 2" ℄	h'_{SO_1}	h'_{SO_2} 1" ℄	h'_{SO_2} 2" ℄	h'_{SO_2} 2 3/4" ℄	h'_{SO_2}	Δp_T	Δp	$\frac{\Delta p}{q_0}$
30.0	19.1	19.1	19.1	-11.2	-11.7	-11.5	-11.5	30.6	25.4	1.895
40.0	25.1	25.3	25.2	-14.7	-15.8	-15.1	-15.2	40.4	32.7	1.760
50.0	32.2	32.4	32.3	-18.5	-20.0	-19.4	-19.3	51.6	42.2	1.810
60.0	37.7	37.7	37.7	-22.4	-23.6	-23.0	-23.0	60.7	49.4	1.750
65.0	41.3	41.3	41.3	-24.4	-26.0	-25.2	-25.2	66.5	54.3	1.795
70.0	43.9	44.3	44.1	-26.3	-27.6	-27.1	-27.0	71.1	57.8	1.790

TABLE XIV
Double Venturi $\Delta p/q_0$
1 5/8 x 3/4 Primary Venturi

h'_s	h'_{SD_1} 1" ℄	h'_{SD_1} 2" ℄	h'_{SD_1}	h'_{SD_2} 1" ℄	h'_{SD_2} 2" ℄	h'_{SD_2} 2 3/4" ℄	h'_{SD_2}	Δp_T	Δp	$\frac{\Delta p}{q}$
30.0	17.0	17.0	17.0	-10.1	-10.7	-10.9	-10.6	27.6	22.4	1.391
40.0	23.0	22.8	22.9	-13.7	-14.1	-14.6	-14.1	37.0	29.3	1.383
50.0	28.2	28.4	28.3	-16.8	-17.7	-18.2	-17.6	45.9	36.5	1.378
60.0	34.0	34.2	34.1	-20.1	-21.0	-21.6	-21.2	55.3	44.0	1.370
65.0	37.0	36.8	36.9	-22.2	-23.5	-23.6	-23.1	60.0	47.8	1.362
70.0	39.8	39.6	39.7	-23.7	-24.8	-25.4	-24.6	64.3	51.0	1.370

TABLE XV
Double Venturi $\Delta p/q$
1 3/8 x 3/4 Primary Venturi

h'_s	h'_{SD_1} 1" ℄	h'_{SD_1} 2" ℄	h'_{SD_1}	h'_{SD_2} 1" ℄	h'_{SD_2} 2" ℄	h'_{SD_2} 2 3/4" ℄	h'_{SD_2}	Δp_T	Δp	$\frac{\Delta p}{q}$
30.0	14.8	14.8	14.8	- 9.5	- 9.1	- 8.7	- 9.4	24.2	19.0	1.062
40.0	20.2	20.0	20.1	-12.8	-12.2	-11.0	-12.0	32.1	24.4	1.012
50.0	25.0	24.8	24.9	-16.2	-15.2	-14.1	-15.1	40.0	30.6	1.023
60.0	30.2	30.0	30.1	-19.2	-17.4	-16.7	-17.8	47.9	36.6	1.012
65.0	32.6	32.6	32.6	-21.1	-19.1	-18.0	-19.4	52.0	39.8	1.022
70.0	35.2	35.0	35.1	-22.8	-20.4	-19.2	-20.8	55.9	42.6	1.022

TABLE XVI
Double Venturi $\Delta p/q$
1 1/4 x 5/8 Primary Venturi

h'_s	h'_{SD_1} 1" ℄	h'_{SD_1} 2" ℄	h'_{SD_1}	h'_{SD_2} 1" ℄	h'_{SD_2} 2" ℄	h'_{SD_2} $2\frac{3}{4}$" ℄	h'_{SD_2}	Δp_T	Δp	$\frac{\Delta p}{q}$
30.0	15.6	15.8	15.7	- 9.9	-10.1	-10.5	-10.2	25.9	20.7	1.202
40.0	21.2	21.4	21.3	-13.4	-13.2	-14.6	-13.6	34.9	27.2	1.182
50.0	26.4	26.2	26.3	-16.3	-16.7	-17.6	-16.9	43.3	33.8	1.182
60.0	31.6	31.4	31.5	-19.8	-20.2	-21.0	-20.3	51.8	40.5	1.172
65.0	34.4	34.2	34.3	-21.6	-21.8	-22.8	-22.1	56.4	44.3	1.185
70.0	36.8	36.6	36.7	-23.4	-23.6	-24.7	-23.9	60.6	47.3	1.185

TABLE XVII
Double Venturi $\Delta p/q$
1 1/4 x 3/4 Primary Venturi

h'_s	h'_{SD_1} 1" ℄	h'_{SD_1} 2" ℄	h'_{SD_1}	h'_{SD_2} 1" ℄	h'_{SD_2} 2" ℄	h'_{SD_2} $2\frac{3}{4}$" ℄	h'_{SD_2}	Δp_T	Δp	$\frac{\Delta p}{q}$
30.0	13.6	13.8	13.7	- 9.9	-10.0	-10.4	-10.1	23.8	18.6	0.948
40.0	18.3	18.3	18.3	-13.4	-13.2	-13.8	-13.5	31.8	24.1	0.934
50.0	22.8	23.0	22.9	-16.6	-16.5	-17.1	-16.7	39.6	30.2	0.929
60.0	27.7	27.7	27.7	-19.9	-19.7	-20.5	-20.0	47.7	36.4	0.938
65.0	30.0	30.0	30.0	-21.8	-21.4	-22.1	-21.8	51.8	39.6	0.951
70.0	32.1	32.1	32.1	-23.2	-23.0	-23.7	-23.3	55.4	42.1	0.937

TABLE XVIII
Double Venturi $\Delta p/q$
1 1/8 x 5/8 Primary Venturi

h'_s	h'_{SD_1} 1" ℄	h'_{SD_1} 2" ℄	h'_{SD_1}	h'_{SD_2} 1" ℄	h'_{SD_2} 2" ℄	h'_{SD_2} 2 3/4" ℄	h'_{SD_2}	Δp_T	Δp	$\frac{\Delta p}{q}$
30.0	15.6	15.6	15.6	- 9.6	-10.0	-10.0	- 9.9	25.5	20.3	1.252
40.0	20.8	20.8	20.8	-12.7	-13.4	-13.6	-13.3	34.1	26.4	1.195
50.0	25.8	25.6	25.7	-16.2	-17.0	-17.1	-16.8	42.5	33.1	1.190
60.0	30.5	30.5	30.5	-19.6	-20.5	-20.7	-20.3	50.8	39.5	1.182
65.0	33.2	33.4	33.3	-21.3	-22.2	-22.5	-22.0	55.3	43.1	1.190
70.0	35.7	35.5	35.6	-23.0	-24.1	-24.0	-23.7	59.3	46.0	1.182

TABLE XIX
Double Venturi $\Delta p/q$
1 1/8 x 1/2 Primary Venturi

h'_s	h'_{SD_1} 1" ℄	h'_{SD_1} 2" ℄	h'_{SD_1}	h'_{SD_2} 1" ℄	h'_{SD_2} 2" ℄	h'_{SD_2} 2 3/4" ℄	h'_{SD_2}	Δp_T	Δp	$\frac{\Delta p}{q}$
30.0	20.4	19.8	20.1	-13.2	-13.9	-13.0	-13.4	33.5	28.3	2.350
40.0	27.0	26.2	26.6	-17.6	-18.6	-16.6	-17.6	44.2	36.5	2.255
50.0	33.5	32.1	32.3	-21.8	-23.1	-21.0	-22.6	54.9	45.5	2.230
60.0	40.0	38.2	39.1	-26.1	-27.8	-25.0	-26.3	65.4	52.1	2.110
65.0	43.2	41.6	42.4	-28.5	-30.3	-27.2	-28.6	71.0	58.8	2.170
70.0	46.7	44.3	45.5	-30.5	-32.1	-29.1	-30.6	76.1	62.8	2.170

TABLE XX
Double Venturi $\Delta p/q$
1 5/8 x 1/2 Primary Venturi

h'_s	h'_{SD_1} 1" ℄	h'_{SD_1} 2" ℄	h'_{SD_1}	h'_{SD_2} 1" ℄	h'_{SD_2} 2" ℄	h'_{SD_2} 2 3/4" ℄	h'_{SD_2}	Δp_T	Δp	$\frac{\Delta p}{q}$
30.0	18.2	18.0	18.1	-10.8	-10.9	-11.3	-11.0	29.1	23.9	1.590
40.0	24.0	24.2	24.1	-14.2	-14.4	-14.8	-14.5	38.6	30.9	1.521
50.0	30.5	30.1	30.3	-18.0	-18.3	-18.7	-18.3	48.6	38.2	1.500
60.0	35.6	35.6	35.6	-21.3	-21.6	-21.8	-21.6	57.2	45.9	1.492
65.0	38.9	38.7	38.8	-23.4	-23.6	-24.1	-23.7	62.5	50.3	1.515
70.0	41.7	41.9	41.8	-24.9	-25.1	-25.7	-25.2	67.0	53.7	1.486

TABLE XXI
Double Venturi $\Delta p/q$
1 1/2 x 3/4 Primary Venturi

h'_s	h'_{SD_1} 1" ℄	h'_{SD_1} 2" ℄	h'_{SD_1}	h'_{SD_2} 1" ℄	h'_{SD_2} 2" ℄	h'_{SD_2} 2 3/4" ℄	h'_{SD_2}	Δp_T	Δp	$\frac{\Delta p}{q}$
30.0	17.5	17.3	17.4	- 9.7	-10.3	-10.1	-10.0	27.4	22.2	1.552
40.0	23.0	22.8	22.9	-13.4	-13.9	-14.1	-13.8	36.7	29.0	1.480
50.0	28.4	28.2	28.3	-16.9	-17.2	-17.3	-17.1	45.4	36.0	1.440
60.0	33.7	33.5	33.6	-20.6	-20.2	-20.9	-20.6	54.2	42.9	1.420
65.0	36.4	36.2	36.3	-21.8	-22.2	-22.6	-22.2	58.5	46.3	1.408
70.0	39.0	39.0	39.0	-23.7	-23.7	-24.1	-23.8	62.8	49.5	1.408

TABLE XXII
Double Venturi $\Delta p/q$
1 3/8 x 5/8 Primary Venturi

Primary Venturi	A_J	$\frac{A_J}{A_D}$	$\frac{u}{U_D}$	h_{gv}	Δp MM. ALC.	Δp MM. H_2O	$\frac{h_{gv}}{\Delta p}$	E.R.
1 1/8 x 1/2	.196	.00693	4.63	682	46.0	37.5	18.20	0.584
1 3/8 x 1/2	.196	.00693	4.24	500	51.2	41.8	11.95	0.351
1 5/8 x 1/2	.196	.00693	4.47	471	62.8	51.2	9.21	0.286
1 1/8 x 5/8	.307	.01085	4.44	727	42.1	34.3	21.20	1.022
1 1/4 x 5/8	.307	.01085	4.19	600	42.6	34.8	17.28	0.784
1 3/8 x 5/8	.307	.01085	4.77	657	49.5	40.4	16.28	0.843
1 1/4 x 3/4	.441	.01560	4.91	785	47.3	38.6	20.30	1.556
1 3/8 x 3/4	.441	.01560	4.99	757	51.0	41.6	18.20	1.415
1 1/2 x 3/4	.441	.01560	4.38	565	53.7	43.8	12.90	0.881
1 5/8 x 3/4	.441	.01560	4.81	610	57.8	47.1	12.96	0.973

TABLE XXIII
Double Venturi Energy Ratio

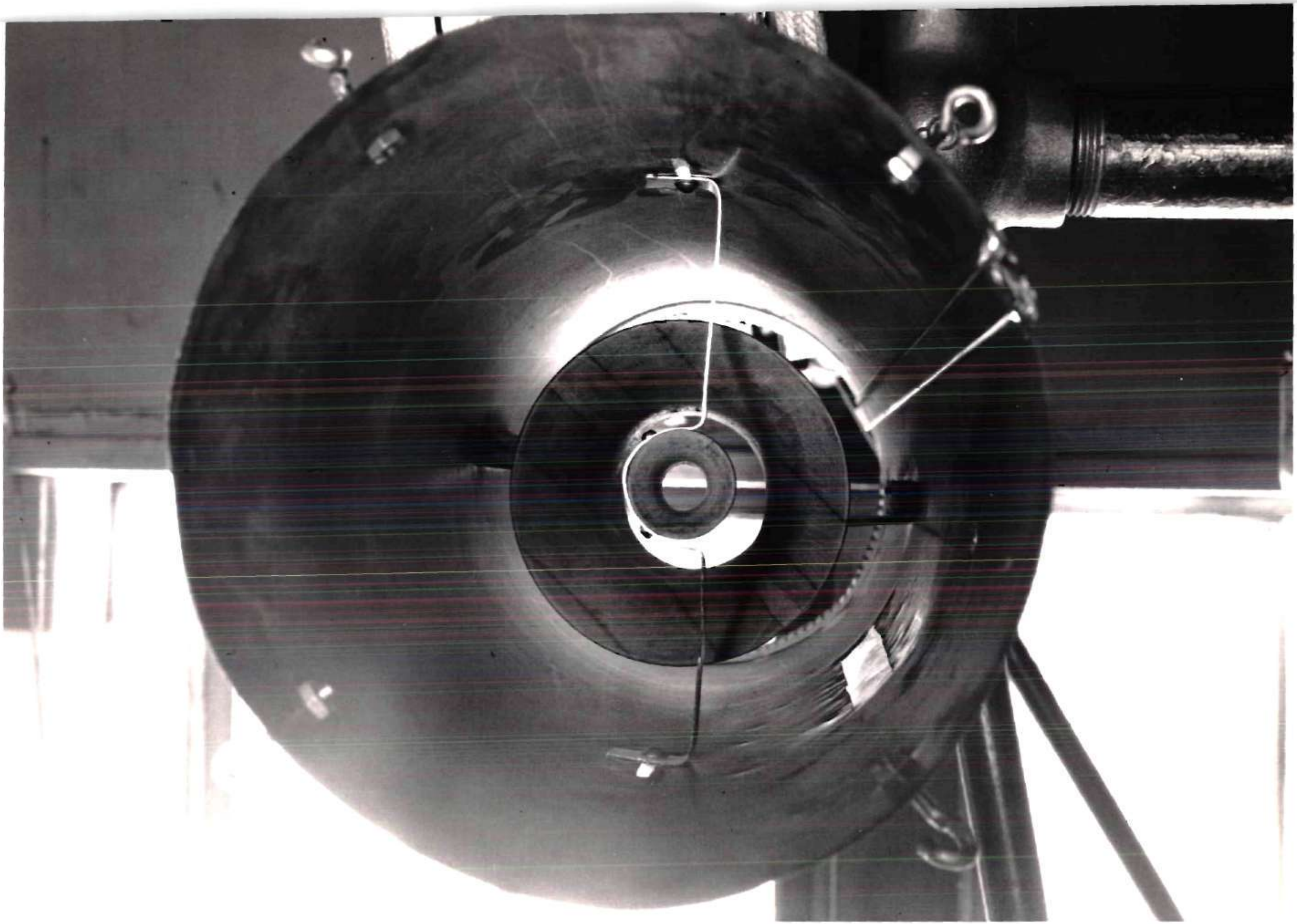


FIG. 1 TYPICAL DOUBLE VENTURI IN DUCT

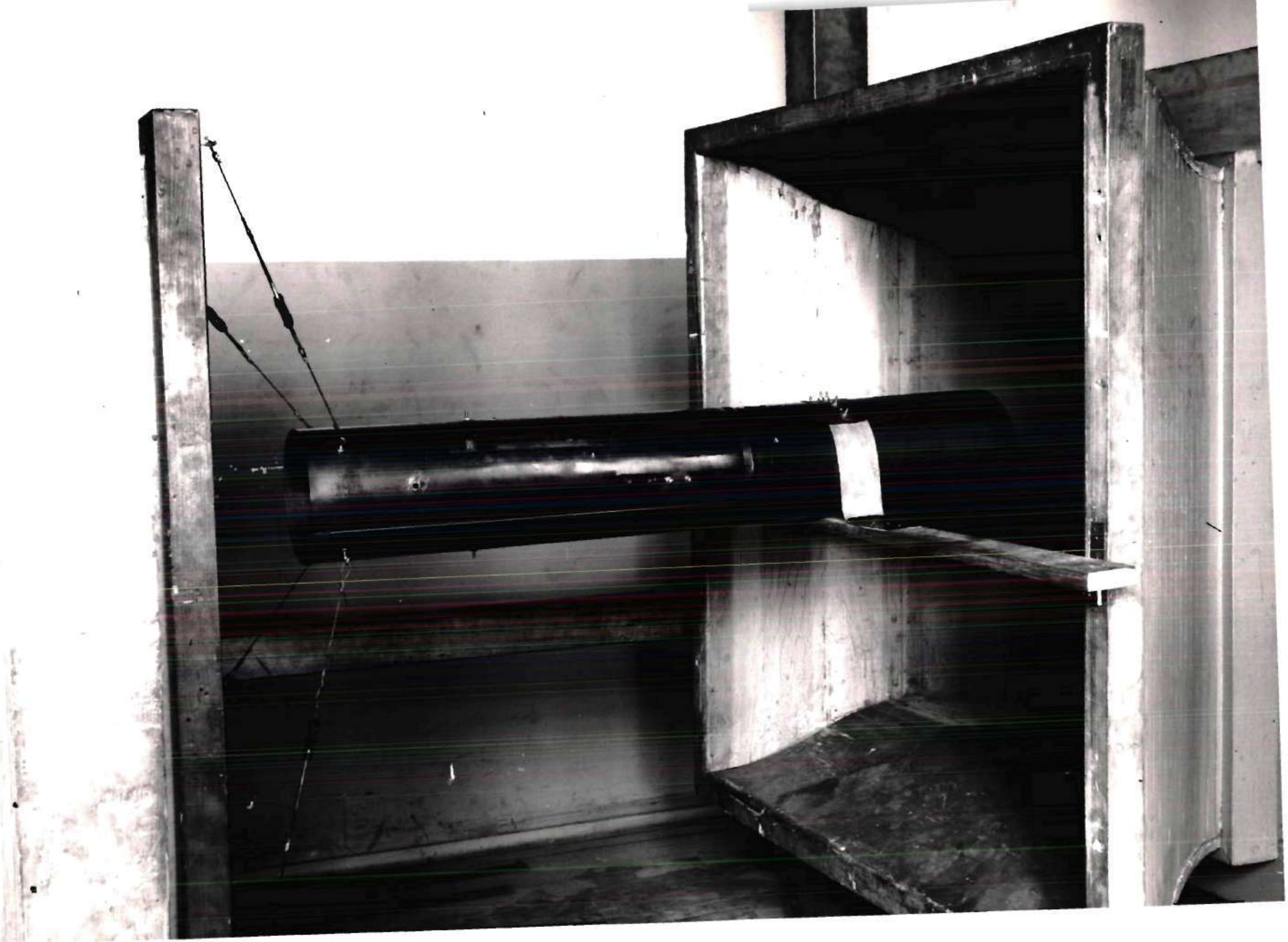


FIG. 2 DUCT IN SMALL TUNNEL TEST SECTION

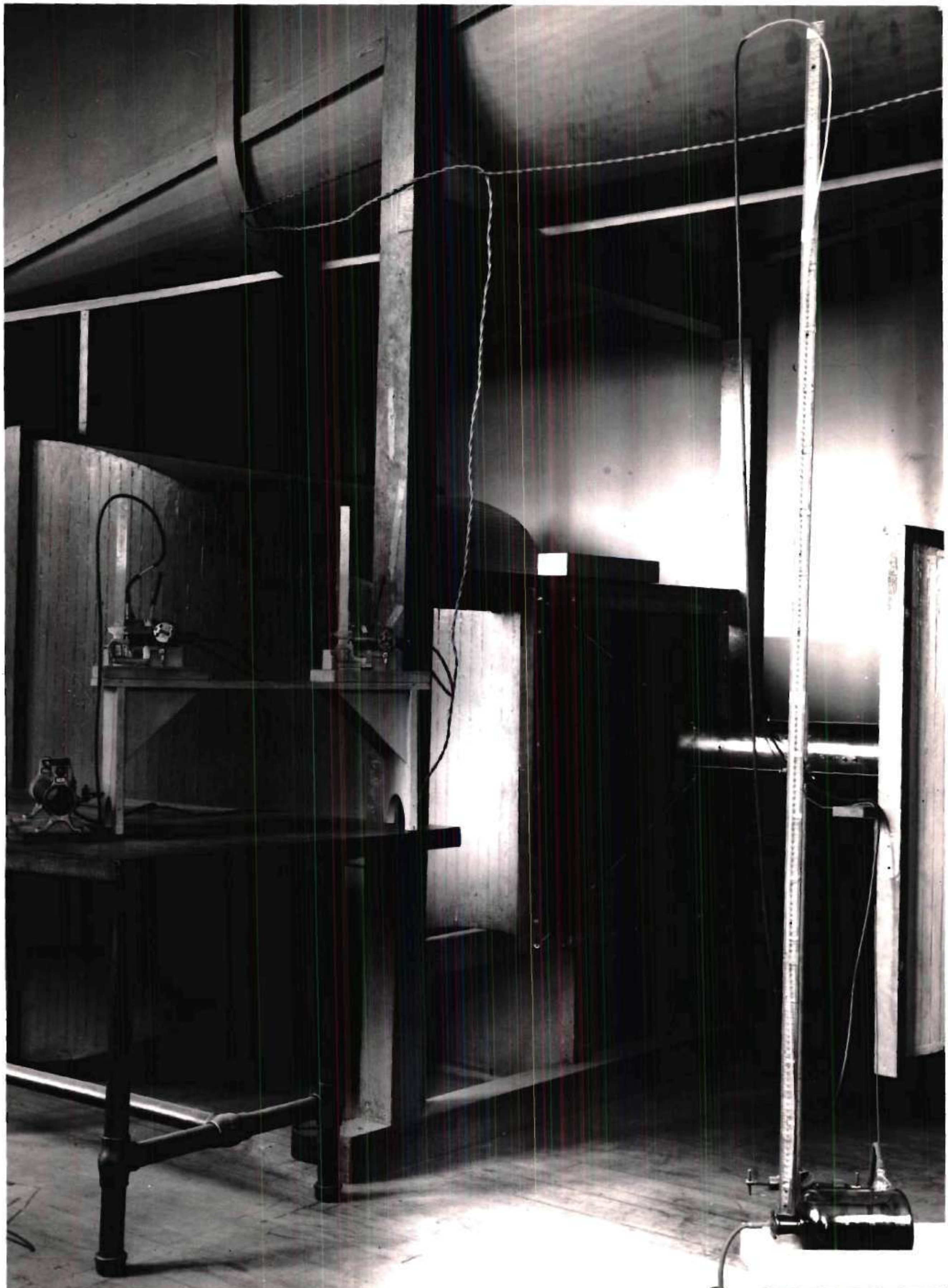


FIG. 3 MEASURING h_{qv}

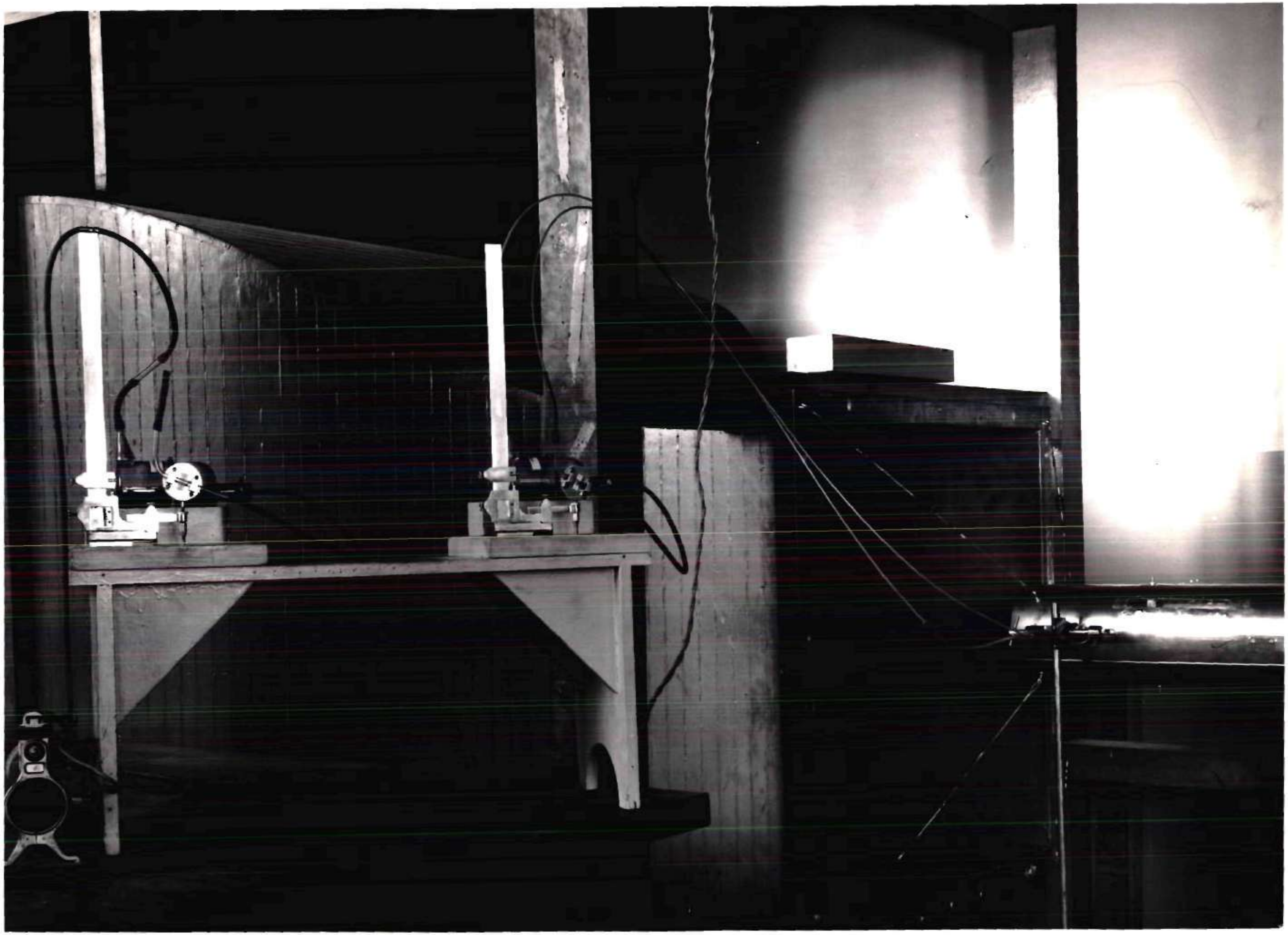
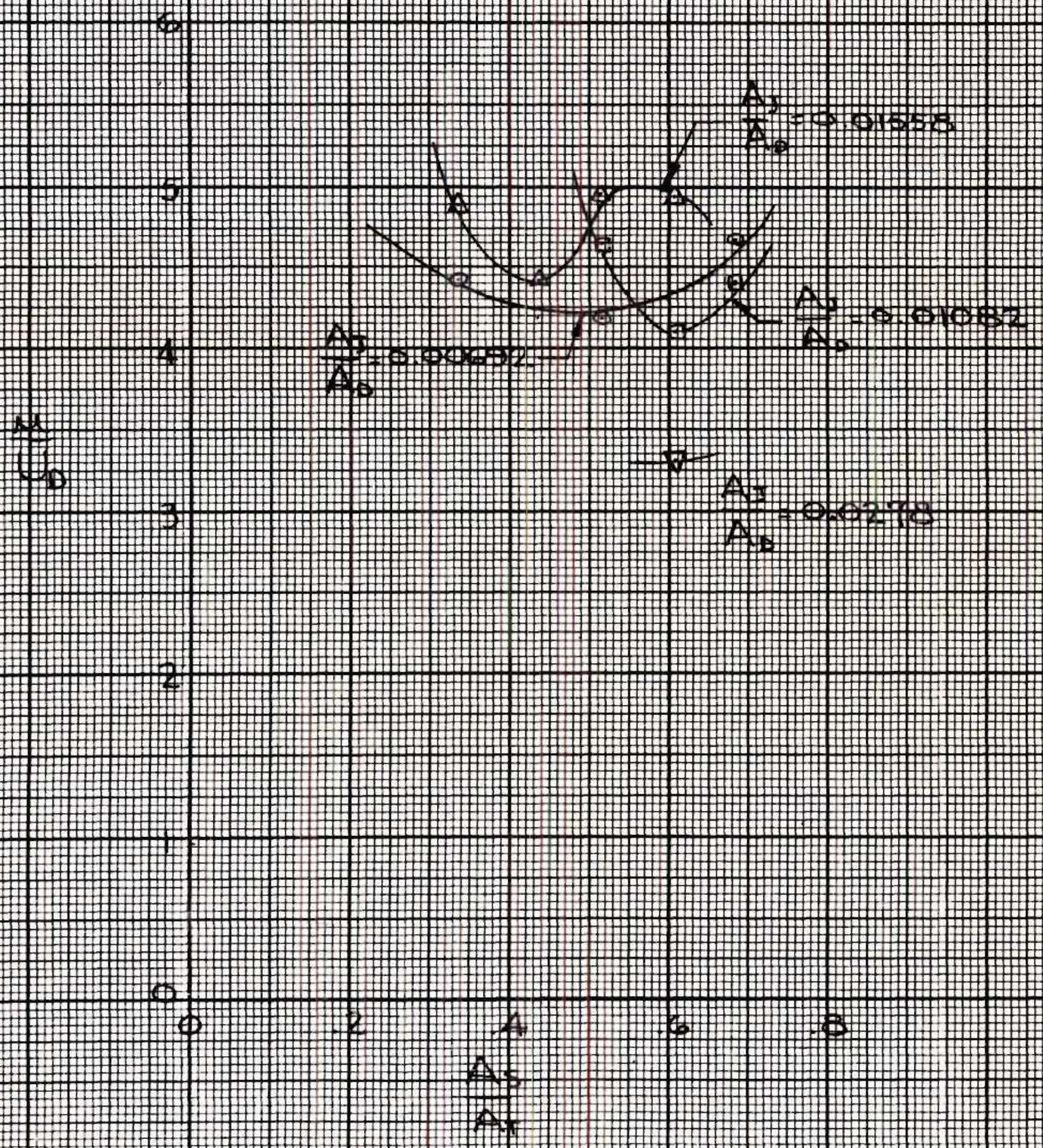


FIG. 4 MEASURING h'_{90}

Fig. 6

Velocity Ratio vs $\frac{A_S}{A_T}$

Double Venturi in Duct



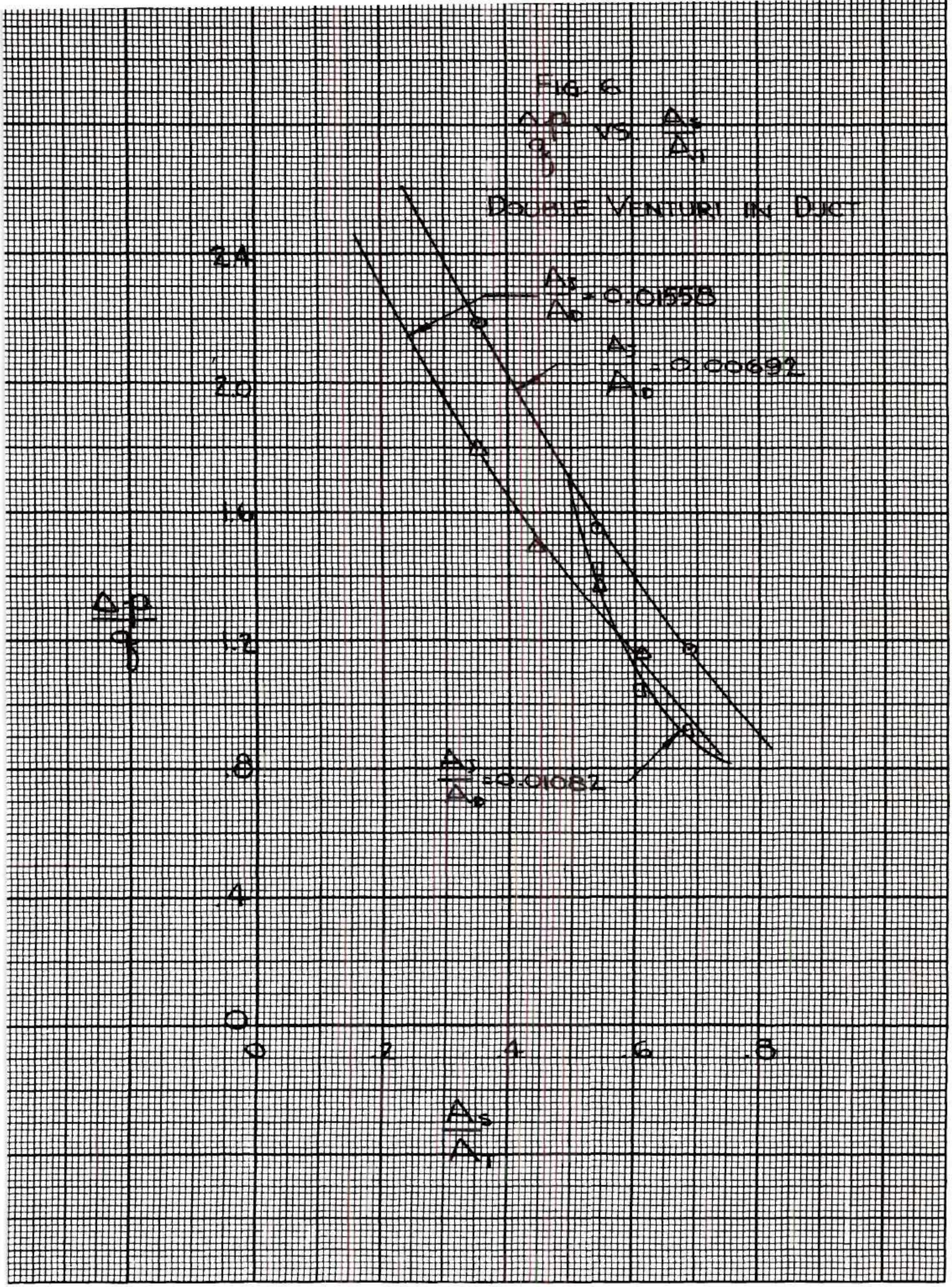


FIG. 6
$\frac{\Delta p}{q}$ VS. $\frac{A_s}{A_1}$
DOUBLE VENTURI IN DUCT
$\frac{A_s}{A_0}$ = 0.01558
$\frac{A_s}{A_0}$ = 0.00692
$\frac{A_s}{A_0}$ = 0.01082
2.4
2.0
1.6
1.2
.8
.4
0
0
.2
.4
.6
.8
$\frac{\Delta p}{q}$
$\frac{A_s}{A_1}$

FIG. 7

ENERGY RATIO VS. $\frac{A_S}{A_T}$

DOUBLE VENTURI IN DUCT